Instrument for Airborne Remote Sensing of Transmission Pipeline Leaks

State-of-the-Art Review
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Introduction

The detection of gas leaks represents a critical operation performed regularly by the gas industry to maintain the integrity and safety of its vast network of piping, both above and below the ground. Below-ground piping includes approximately 400,000 miles of transmission pipelines and 1.4 million miles of distribution piping, while above-ground piping is located mainly at about 750 gas processing plants and some 3000 compressor stations. Whether addressing above or below ground gas sources, leak surveying with state-of-the-art gas detectors can be a time-consuming operation of uncertain effectiveness.

For surveys of buried piping, state-of-the-art natural gas leak detectors employ a flame ionization detector (FID). A sampling pump in the unit continuously withdraws, or "sniffs," samples of the ambient air and delivers them through a sampling probe to the flame ionization sensor itself. The surveyor scans the ground, carrying the sampling probe barely above ground level. The probe must be brought fairly close to the leak vent to sample detectable quantities of gas. To find a leak quickly the surveyor must possess enough experience to know where to look. Complicating matters somewhat is the underground migration of leaking gas from buried pipes, causing the gas to reach the surface at some location often not apparent to the surveyor. Leak surveys with an FID can cover 8-10 miles per day in the man-portable mode, and slightly more in a vehicle-mounted mode. As an alternative to using an FID, low-flying aircraft are sometimes used to discern discolored vegetation caused by the gas leaks. This technique obviously cannot be used in areas without sufficient vegetation, such as the desert and steppe areas or during the winter.

As an example of an advanced leak-detection approach, Boreal Laser (Spruce Grove, Canada) uses an air-sampling laser-based gas sensor for pipeline monitoring that requires the aircraft to fly through the methane plume. Sampling the air significantly above the ground surface relies upon diffusion of the plume into the aircraft flight path. This technique is thus adversely affected by plume dilution and advection away from the pipe.

New Detection Technology

Based on these considerations, it would be desirable to deploy a remote pipeline inspection instrument on an aircraft that could detect the leak remotely without physically sampling the air above the leak. There are two alternatives for such remote sensing techniques: (1) active detection, which requires illuminating the scene with a radiation source, usually a laser, that is absorbed by the target gas, and (2) passive detection (also called thermal detection), which relies on radiative transfer due to a temperature and/or emissivity difference that usually exists between the background and the target cloud (see Fig. 1). While passive methods allow nearly unlimited range with a simple instrumental configuration, these methods rely upon a thermal flux between the plume and the ground surface below it. Active detection removes the thermal constraint, but requires a laser and a scattering surface behind the gas for generation of the signal. It also has a relatively lower operational range.

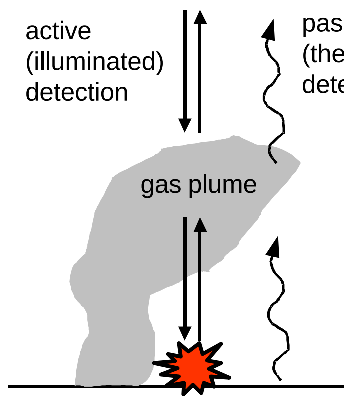

Fig. 1. Illustration of active and passive detection systems.

Because there are clear differences between active and passive optical detection approaches, over the past year we have examined the merits of each method for the particular problem of detecting natural gas leaks in transmission pipelines. This required developing a complete model of the measurement processes for active and passive techniques against the ground surface. We could then compare the results of these predictions with experimental studies of breadboard active and passive systems we have developed in our laboratory. While the breadboard systems were not optimized for long-range detection of methane leaks, they served as a check for the theoretical predictions that could then be extrapolated for further standoff distances.

The sensitivity of remote gas detectors is dependent on the integrated column density of the gas, which is the product of the concentration of the target gas (ppm) and the thickness of gas plume (m). This is often termed the CL product. We then define the noise equivalent concentration-length product (NECL) as the CL product producing a signal-to-noise ratio of unity. The lower the NECL, the more sensitive the detection scheme. Beyond determining the NECLs for active and passive systems, we have also predicted gas concentrations and geometries expected from transmission pipeline leaks. This provided the CL products it would be necessary to detect. In addition, for passive detection, we have examined the signal source term, using pairs of thermistors to measure temperature differences between the ground and the air under different weather conditions.

Based on the past year's study, we have chosen an active method as the optimum approach to detect natural gas leaks from a low-flying aircraft. The passive detection limit is ultimately governed by the magnitude of the energy transfer between the gas plume and the ground surface. Given a modest typical temperature difference of 5^{o}C between the ground and the air above the ground, the experimentally confirmed calculations predict that an active approach will be an order of magnitude more sensitive to detect natural gas leaks.

Definition of Problem

The routine inspection of transmission pipelines poses additional challenges for gas leak detection because of the large standoff distances required for airborne platforms. Remote detection of these leaks will likely require sweeping over the area of interest to acquire an image of the methane concentration at the ground surface. For active detection, this can be accomplished by either dithering a laser beam back and forth across the field of view or by spreading the laser beam so that it encompasses the necessary field of view. Because of the speed of airborne travel, the acquisition must be performed at a rapid rate to cover the required ground space within the area of interest.

For analysis of airborne remote leak detection, we will begin with the operational parameters of the low-flying aircraft used to discern discolored vegetation. This is illustrated in Fig. 1. It was reported by industrial representatives that aircraft fly at an altitude of ~200 m at a speed of ~120 mph for detection of discolored vegetation. For remote optical detection of methane, we assume that we will probe a 10-m side-to-side area at a resolution of 0.5-m.

Remote detection of transmission pipeline leaks will likely require sweeping the detector field-of-view (FOV) over the area of interest to acquire an image of the integrated methane concentration between the aircraft and the ground surface. For active detection, this can be accomplished by either dithering a laser beam back and forth across the field of view, often referred to as raster scanning, or by spreading the laser beam so that it encompasses the necessary field of view, referred to as pushbroom acquisition (see Fig. 3). For passive detection, the imaging scenario will require frequent acquisition of the field of view by, for example, a linear array detector. Because of the speed of airborne travel, the acquisition must be performed at a rapid rate to cover the required ground space within the area of interest. For a raster-scanning measurement at 120 mph, the FOV must be swept between measurement pixels at a rate of 2140 Hz. For pushbroom acquisition, this data rate is lowered by a factor of 20 to 107 Hz.

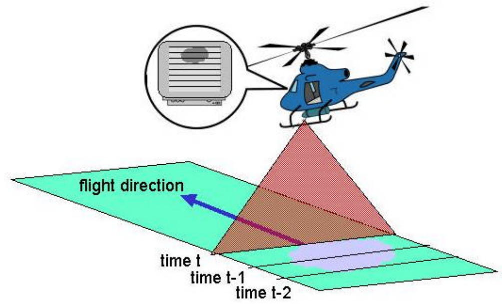

Fig. 2. Airborne platform for detection of gas leaks

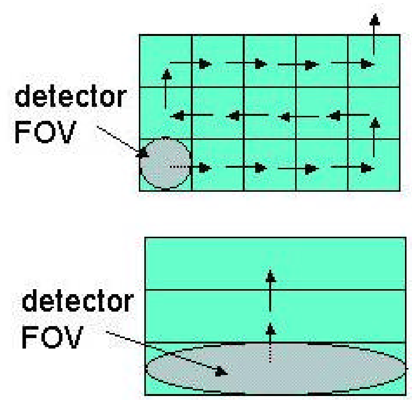

Fig. 3. Detection scenarios with raster scanning of FOV (above) and pushbroom acquisition (below).

Passive Detection Systems

Passive infrared detection systems have been developed to view chemical plumes, and such imagers are offered commercially (e.g., Physical Sciences Inc., Andover, MA). One of the main advantages of passive techniques is that they do not require a background from which to scatter radiation. This is not such an advantage for an airborne system, however, because the ground serves as a backscatter surface. In addition, since passive methods require a temperature/emissivity difference with the background, the detected gas will appear invisible at the temperature for which there is no net radiative heat transfer between the gas and the surroundings.[1] For the analysis of passive detection systems, we considered a spectral filtering system optimized to the different absorption features of methane.

Active Detection Systems

Due to the development of laser sources emitting wavelengths in hydrocarbon absorption bands, active laser-based methods have recently been applied to the detection of methane. Many of these devices are based on point-detection methods, for which the laser return signal is collected on a single detector. These techniques can be extended to wide area coverage by implementing them with scanning optics. For example, SRI International (Menlo Park, CA) has developed a vehicle-mounted gas point-detection system with a scanning optical head.[2] Pulsed differential absorption lidar systems have also been developed for remote point-detection of methane leakage.[3,4] In addition, continuous-wave (cw) diode lasers with frequency modulation (FM) can be implemented into optical gas detection systems.[5,6]

Laser Imaging Systems (Punta Gorda, FL) provides a commercial version of a gas imager based on backscatter absorption gas imaging (BAGI) using cw CO_2-laser illumination.[7] LaSen (Las Cruces, NM) has also developed a gas imager based on pulsed laser illumination. For backscattered imaging, cw imagers work by scanning both the laser and the detector field of view back and forth over the scene, while pulsed imagers work by flooding the scene, or a particular fraction of the scene, with laser radiation, and taking a snapshot of the illuminated area. Based on the BAGI technique, Sandia National Laboratories (SNL) has developed a variety of active imaging systems for the detection of gas leaks. These imagers have encompassed both short-range (≤20 m) systems on person-portable platforms[8] and long-range (≤300 m) systems[9] more suited to vehicle or airborne platforms. SNL has incorporated both cw lasers and pulsed lasers[10,11] into their imagers. For the analysis of active systems, we considered topographic differential backscatter using a pulsed laser source.

Considered Alternatives

In considering alternative approaches, we will term the techniques described thus far as the baseline detection scenarios. The baseline passive technique is therefore to use a filter or dispersive grating to detect passive radiation from two closely spaced wavelengths, one of which includes the absorption feature of the gas to be detected. The baseline active technique is topographic differential backscatter using a pulsed laser source.

The *Michelson Interferometer-Spectrometer*, or *FTIR*, have been shown to possess the ability to capture a single spectrum at sufficient spectral resolution for methane detection in ~1 sec, which would not be suitable for airborne detection for which we need to acquire data at ~100 Hz.

Laser heterodyne techniques can be used to reach the shot-noise limit, but have limited throughput. These techniques operate by mixing a local oscillator (e.g., a modulated laser source) with the active or passive radiation that is captured by the detector. For optimized performance, the receiver should collect only a single speckle cell. This decreases the throughput by a large factor. If we define the throughput by $Th = A_C \Omega_C$, where $\Omega_C = \pi \theta_{1/2}^2$, and the size of a speckle cell is $\lambda^2 / \pi \theta_{1/2}^2$, then the optimal throughput for a laser heterodyne receiver is given as λ^2. In comparison with the baseline systems, the throughput is decreased by three orders of magnitude at 3 µm. Calculations have shown that this would have an overall negative effect on the system detection limit. Heterodyne detection in the long-wave IR could be beneficial, however, because of the increased allowable throughput (because • is larger) and the increased thermal flux at this wavelength range.

Gas correlation spectroscopy can be used for either passive or active sensing to separate the wavelengths absorbed and unabsorbed by the probed gas. It works by having two detector legs, one of which has a gas cell with the absorbing species in the path. When the signal returns, it is split between the two legs, and the difference between the signals is recorded. For active techniques, this approach is useful when the source is broadband and you are attempting to isolate the components of the radiation that are absorbed and not absorbed. This eliminates noise from laser energy fluctuations and reduces the need to have successive pulses temporally closely spaced. However, spreading the spectral shape of the pulse over a wavelength range both absorbed and unabsorbed by the target gas significantly decreases the SNR acquired at both wavelengths. Minato et al.[12] report a methane NECL of 88 ppm-m for averaging the return signal from eight laser pulses. Similarly, in a passive approach, the technique sacrifices the potential detection limit for the advantage of simplicity. Sandsten et al.[13] report a detection limit of 200 ppm-m of ammonia (a strong infrared absorber) with a temperature difference of 18 K and a 15 Hz acquisition rate. Gasoptics (Lund, Sweden) is currently marketing a device based on passive gas correlation spectroscopy as a method for detecting gas leaks.

Depending on the primary source of noise, *frequency modulation (FM)* can increase the SNR of absorption signals by many orders of magnitude. A full comparison of FM spectroscopy with the baseline case is difficult, because FM detection of methane is generally performed with diode lasers operating in the near-IR telecommunications wavelengths[14] (~1.6 µm). The absorptivity of methane at these wavelengths is a factor of 100 less than the absorptivity in the mid-IR. For a full discussion of the application of FM methods with remote sensing, the reader is referred to the paper by Dubinsky et al.[15] A recent study by Wainer et al.[6] displayed an NECL of 12 ppm-m for a 30-m standoff distance and a 1-sec acquisition time.

Future Directions

The Remote Sensing Group at SNL is currently involved in a number of activities relating to standoff leak detection for different gas industry sectors. These efforts stem from original investments made by the DOE Office of Fossil Energy (FE). We are funded by the Department of Energy's FE program and Office of Industrial Technology (OIT) to develop a person-portable shoulder-mounted gas imager for use at oil refineries. We are also funded by the Japan Gas Association (JGA) through the Gas Technology Institute (GTI, Des Plaines, IL) to develop a smaller handheld gas imager for natural-gas leak detection in and around homes in Japan. With additional support from DOE/FE and GTI we are developing a vehicle-mounted laser-based mapping procedure that can detect gas-plume concentrations near the operational threshold an FID. With this experience we are well positioned to design and construct an airborne remote sensing instrument for detection of natural gas leaks. In 2003 a remote-sensing instrument with the performance requirements for long-range airborne testing will be demonstrated. The system will then be ruggedized sufficiently for an airborne test and an airborne test will be performed the following performance period.

Acknowledgements

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